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Influence of Ground Station Number and its Geographical Distribution on Combined Orbit Determination of Navigation Satellite

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Abstract

Using combined orbit determination based on satellite crosslink ranging observations, navigation system could greatly reduce the dependence of ground stations. In this paper, a constellation constituted by 24MEO+5GEO+3IGSO was simulated considering the characteristics of the second generation of BD (COMPASS), then corresponding simulated combined orbit resolution has been done using this kind of constellation. We implemented analyses from aspects of different ground station number and geographical distribution to investigate their influence on combined orbit determination (COD). Results show that well-distributed stations around the world do a little better orbit determination performance than that with stations of regional distribution in China. Besides, accuracy could be slightly better than precision of broadcast ephemeris only using just one station inside our country. Nevertheless, increase in the number of stations could not significantly improve the COD accuracy when all stations are located regionally at home, however, it could enhance the stability and reliability of the navigation system.

Keywords: Broadcast ephemeris; Navigation system; Combined Orbit Determination; Ground station; Satellite Crosslink

Introduction

As an important kind of data to navigation and real-time positioning, broadcast ephemeris is traditionally generated by long-time tracking, orbit determination and forecasting of ground operational control segments toward navigation satellite[1,2]. Its precision is ensured by enough number of ground stations with well geographical distribution[2,3]. However, because of limited land area, it is difficult for a country to satisfy such condition, and there are lots of complex political factors need to be considered when building stations in other countries.

In fact, U.S.A set about investigating equipping crosslink on navigation satellite since GPS establishment began for navigation satellites, with the capability of crosslink ranging and data transmitting

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could not only form autonomous navigation (Autonav) system during wartime quickly, but also solve the difficulty of uniformly setting up ground stations worldwide using COD method during peacetime[3-8].

M.P.Ananda proposed the concept of GPS Autonav with satellite crosslink and implemented preliminary research on its feasibility in 1980s[4]. LIU et al. (2000) proved the effectiveness of COD using both satellite-satellite tracking data and ground based tracking data through numerical analysis, taking LEO satellites as example[9]. By combining space-borne GPS data of LEO satellites and ground tracking observations, Geng et al. (2007) illustrated that the COD of GPS observations was superior to the orbit determination only using ground tracking observations[10]. Based on the theory and methodology of AutoNav and the traditional ground-based orbit determination, Liu (2008) also discussed and analyzed the feasibility and advantage of the COD using both ground and crosslink ranging data in detail[3]. Geng et al. (2010) conducted COD of simulated COMPASS. Results indicated that the navigation system combining ground tracking observations with inter-satellite crosslink could reduce the dependence of ground station number and its distribution[7]. Using constellation constituted only by MEO satellites, Liu et al. (2010) illustrated that this kind of navigation system could reduce the dependence of ground station number and its geometric distribution when COD was applied. However, increase in the number of stations and better geographical distribution could not significantly increase the orbit accuracy[8]. Based on the above research, this paper mainly analyzed the influence of ground station number and its geographical distribution on COD. Taking into accounts the characteristics of the second generation of BD (COMPASS), constellation simulated in this paper includes MEO satellites, GEO satellites and IGSO satellites. Some useful conclusions have been drawn at the end of this paper.

Function Model

Observation error equation of satellite-satellite range. Before processing inter-satellite observation data, preprocessing of the two-way range observable should be implemented, Which mainly includes tropospheric delay correction, signal transmitting and receiving delay correction, pseudorange smoothing, observation time correction, post-Newtonian effects delay correction, as well as antenna phase center offset correction, etc, so as to obtain the corrected pseudorange. The inter-satellite observation data simulated in this paper refers to the corrected pseudorange.

The Corrected pseudorange equation between satellites can be expressed as[3,5,11]:

$$\rho_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} + c \cdot (\delta t_j - \delta t_i) + \delta_{residual} + \varepsilon_{ij} \tag{1}$$

Where x_i, y_i, z_i denotes the coordinate of SV i, x_j, y_j, z_j is the coordinate of SV j, δt_i and δt_j represent clock error of SV i and SV j, $\delta_{residual}$ is the residual systematic error resulting from incompleted model correction, and ε_{ij} indicates the random noise.

Observation error equation of satellite-ground range. Observation error equation of satellite-ground range is similar to that of satellite-satellite range with the only difference that changing the receiver terminal from satellite to ground station. The equation is omitted here because of limited space. Readers can refer to literature 3 and 8 for detail information.

Parameter estimation method. There are usually two methods for parameter estimation in orbit determination. One is filtering method which solves parameters epoch by epoch. The other is least square method solving the unknown parameters in whole scale during an observation session. Considering computational efficiency and investigation convenience, the second method is chosen in this paper. Readers can refer to literature 3 for more details of these two methods.

Orbit determination software. For the sake of satisfying the investigation requirement, an analysis software package of COD has been developed based on Visual C++. It can be used for orbit determination and prediction with main functional modules including perturbation calculation, orbit integration and prediction, error correction, parameter estimation together with accuracy assessment module. Ground tracking observations and inter-satellite observations were all simulated in this paper.

Generation of simulated observation

Construction of simulated navigation satellite constellation. Considering the characteristics of COMPASS[12], the constellation simulated in this paper includes 24 MEO satellites, 5 GEO satellites and 3 IGSO satellites. The altitude of MEO satellite is 21500km and the inclination is 55° . 24 MEO satellites compose a constellation of Walker24/3/2. Central longitudes of these five GEO satellites are 58.8° 、80° 、110.5° 、140° and 160° . Three IGSO satellites, which refer to geostationary satellites, uniformly distribute in three planes, with the inclination as 55°and the longitude of ascending node is 118°. Initial orbit value of the above constellation were simulated by STK software, which then could be used to simulate observations as the initial value of orbit integration and satellite ephemeris.

Generation of navigation satellite ephemeris. With the initial orbit state (position, velocity, etc.) at time t0 and the necessary perturbation forces (earth gravitation, the third body gravitation, solar radiation pressure, solid earth tide and ocean tide, etc.), an instantaneous state at each sampling epoch could be calculated through numerical integration. At the same time, clock error at each sampling epoch was simulated based on clock model provided by IGS. Afterward, ephemeris could be generated as reference of observation simulation and accuracy analysis.

Generation of inter-satellite observation and ground tracking observation. Inter-satellite observation was simulated by TDMA, where every satellite was assigned 1.5s for transmitting signal, during which the propagation time of signal, satellite clock error and post-Newtonian effects delay has been taken into consideration. Satellite's local time of signal transmitting and receiving were also given along with inter-satellite pseudorange observation. Systematic error and measurement noise were added into both inter-satellite observations and ground tracking observations, of which the systematic error refer to the residual bias resulting from unmodeling or incomplete modeling of observations. Values of systematic error were taken from literature 6, including the fix bias and cyclic error. Noises of inter-satellite observation and ground tracking observation were taken as 50cm and 30cm respectively.

In this paper we simulated three kinds of inter-satellite crosslink: MEO-MEO, MEO-GEO and MEO-IGSO, with the beam angle of transmitting antenna of satellite is taken as 30~60° and the cutoff angle of receiver on the ground is 10°. For more details about how to generate simulated observation, readers can refer to literature 13.

Analysis of simulative calculation

Cases and calculation strategy. In order to better analyze the influence of the ground stations distribution on COD, this paper designed 24 cases as shown in Table 1 from two aspects: different station number and different geographical distribution. For illustration convenience, some cases were repeated. Based on the 24 cases, COD for the constellation from DOY71 to DOY77 of 2007 had been done, then we analyzed the result of each case according to the method demonstrated in the previous section.

Table 1 Case description

Case	Station Num	Station list	Clock Fixed station
1	34	As shown in Fig. 1	ALGO
2	17	As shown in Fig. 2	ALGO
3	5	BJFS+WUHN+KUNM+URUM+LHAZ	BJFS
4	4	BJFS+WUHN+KUNM+URUM	BJFS
5	3	BJFS+URUM+WUHN	BJFS
6	2	BJFS+URUM	BJFS
7	1	BJFS	BJFS
8	1	BJFS	BJFS
9	1	WUHN	WUHN
10	1	LHAZ	LHAZ
11	1	KUNM	KUNM
12	1	URUM	URUM
13	2	BJFS+KUNM	BJFS
14	2	BJFS+URUM	BJFS
15	2	BJFS+LHAZ	BJFS
16	2	BJFS+WUHN	BJFS
17	2	WUHN+URUM	WUHN
18	3	BJFS+KUNM+URUM	BJFS
19	3	BJFS+LHAZ+URUM	BJFS
20	3	BJFS+WUHN+URUM	BJFS
21	3	WUHN+KUNM+URUM	WUHN
22	4	BJFS+WUHN+LHAZ+URUM	BJFS
23	4	BJFS+KUNM+LHAZ+URUM	BJFS
24	4	BJFS+WUHN+KUNM+URUM	BJFS

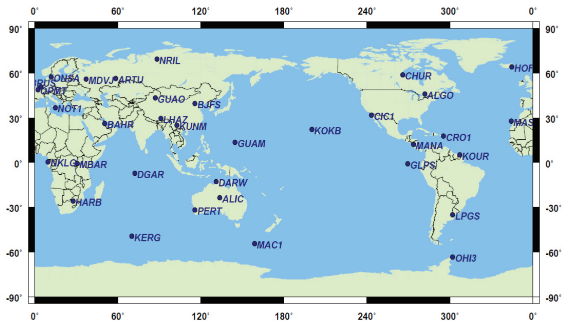

Fig.1 Distribution map of 34 stations

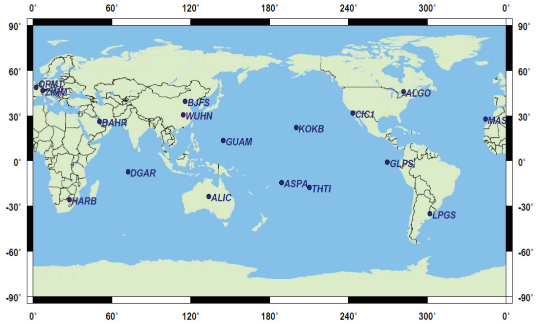

Fig.2: Distribution map of 17 stations

COD result analysis

Influence of different station number on COD. In order to analyze the influence of different number of stations on COD, we determined the orbit for 7 days according to case 1 to case 7. Statistics of 7 days' overall average orbit and clock error RMS and single day's RMS from DOY71 to DOY77 were shown in Fig.3 and Fig.4.

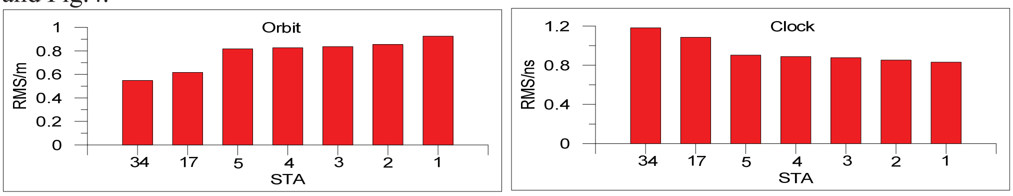

Fig.3 The average RMS of 7 days with different numbers of stations

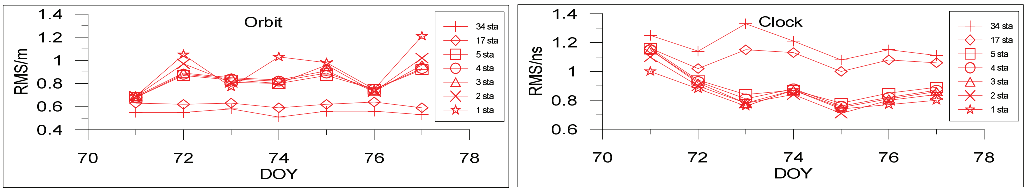

Fig.4 The average RMS of single day with different numbers of stations

From Fig.3 and Fig.4, we could see that orbit determined by 34 stations and 17 stations around the world were a little more precise and stable than that by stations inside the country and the difference between each day's RMS was also smaller. However, clock error determined by stations uniformly distributed around the world was a little weaker, which mainly due to the weaker geometric structure of ground tracking observation than that of inter-satellite observation, for increase of the ground tracking observations would affect the geometric structure of clock error. However, the RMS of orbit and clock error determined by different number of stations inside the country is not much different. In other words, increase in the station number could not obviously improve the COD accuracy little if all selected stations were inside the country. The orbit RMS can reach 1m and clock RMS can reach 1ns with only one station.

Influence of different geographical distribution of stations on COD. The influence of different number of stations on COD has been presented in the previous section. In order to analyze the influence of different geographical distribution of stations, orbit were determined with 1 station, 2 stations, 3 stations and 4 stations in the country by different combinations based on cases shown in Table 1.

A. Result of COD with one station

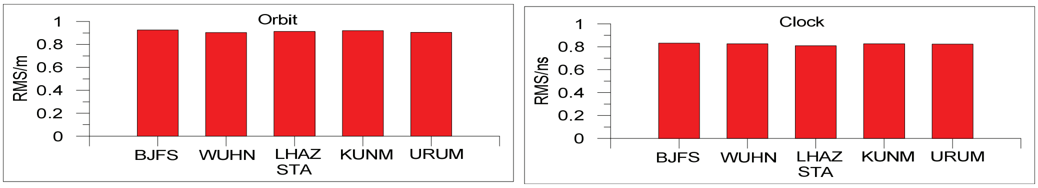

Fig. 5 The average RMS of 7 days with one station

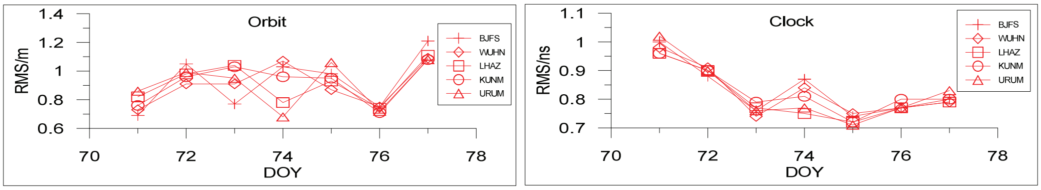

Fig.6 The average RMS of single day with one station

Fig.5 and Fig.6 indicated that 7 days' average orbit and clock error RMS could reach 1m and 1ns with different single station respectively while RMS of single day had some certain differences from DOY71 to DOY77.

B. Result of COD with two stations

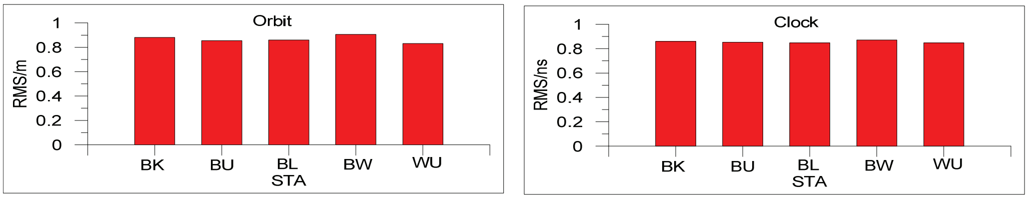

Fig.7 The average RMS of 7 days with two stations with different combinations

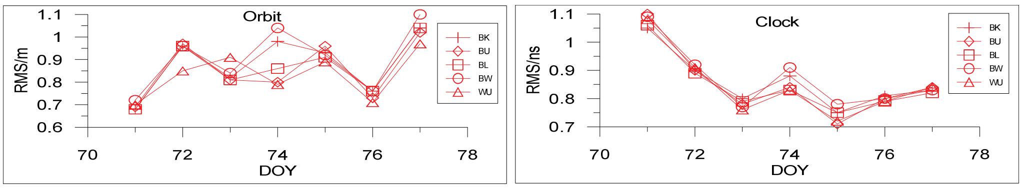

Fig.8 The average RMS of single day with two stations with different combinations

In Fig.7, the characters on abscissa axis denoted the abbreviations of station names. For example, BK represented BJFS and KUNM, the same as below. Fig.7 and Fig.8 indicated that the average orbit and clock error RMS of 7 days could reach 1m and 1ns with two stations respectively, while RMS of single day had some small differences from DOY71 to DOY77. However, the differences are smaller than that COD with single station.

C. Result of COD with three stations

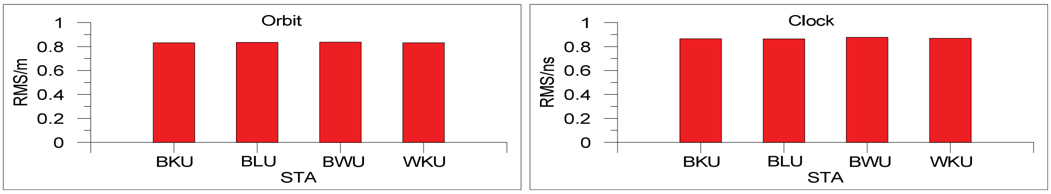

Fig.9 The average RMS of 7 days with three stations with different combinations

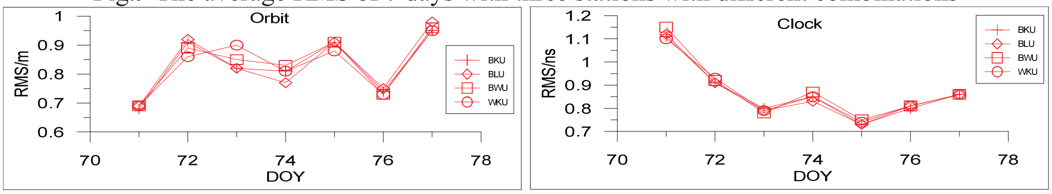

Fig.10 The average RMS of single day with three stations with different combinations

Fig.9 and Fig.10 showed that the average orbit and clock error RMS of 7 days could reach 1m and 1ns with three stations respectively, and the stability of single day's result was further enhanced.

D. Result of COD with four stations

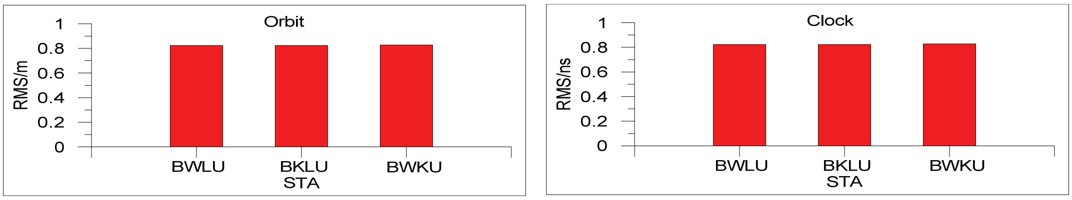

Fig.11 The average RMS of 7 days with four stations with different combinations

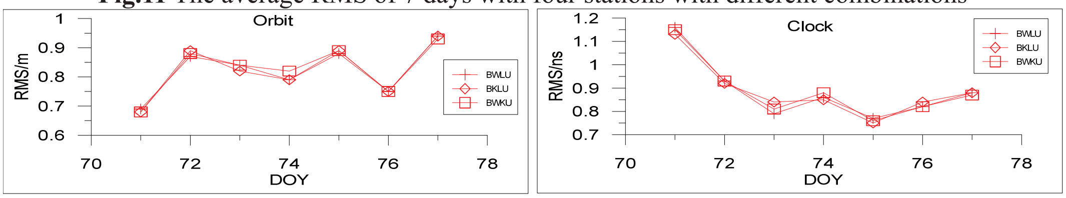

Fig.12 The average RMS of single day with four stations with different combinations

From Fig.11 and Fig.12, we could see that the average orbit and clock error RMS of 7 days could reach 1m and 1ns respectively with four stations, and the stability of single day's result was further enhanced.

From the above analysis, we could see that the effect of different geographical distribution was very limited to COD if ground station number were certain. However, the stability of single day's result was enhanced when increasing the number of ground stations.

Conclusions

According to the characteristics of COMPASS, this paper simulated a constellation consisting of 24 MEO satellites, 5 GEO satellites and 3 IGSO satellites together with its corresponding inter-satellite crosslink observation, ground tracking observation and satellite ephemeris. Through analyzing COD with different number and geographical distribution of ground stations, some useful conclusions has been drawn:

1) Based on the simulated constellation, the COD results with 34 stations and 17 stations around the world were a little better than that with number of stations inside the country and the single day results were more stable.

2) The orbit RMS could reach 1m and the clock error RMS could be 1ns with only single station inside the country, which were a little better than the precision of broadcast ephemeris.

3) When all stations were located inside the country, improvement was not obvious by increasing the number of stations. However, it could enhance the stability of single day's result. In other word, it was helpful to enhance the stability and reliability of navigation system.

4) If the number of stations were certain, COD differences of orbit and clock error were very small with different geographical distribution inside the country.

Ground station is very important to navigation system. Through the above analysis, for the simulated constellation in this paper, we could conclude that it is helpful to achieve more accurate results when implementing COD with 3~5 stations in China, which could also enhance the stability and reliability of navigation system. As for the constellation were simulated based on the characteristic of COMPASS, results in this paper could provide reference to the COMPASS investigation.

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